US Army Corps
of Engineers

Formulation of Sediment Budgets at Inlets

by Julie Dean Rosati and Nicholas C. Kraus

PURPOSE: The Coastal Engineering Technical Note (CETN) herein discusses the steps required for developing a sediment budget in coastal reaches that include inlets. The types of data sets and analysis procedures useful in formulating sediment budgets are addressed, as well as a methodology for incorporation of both quantitative and qualitative data. A sediment-budget methodology for inlets and adjacent beaches is presented, and its application is illustrated through an example. This (September 1999) revision supercedes the previous CETN and contains recent developments from the Coastal Inlets Research Program. The revision expands the methodology for formulating sediment budgets along coasts that include inlets, and additional notation and terminology are introduced.

BACKGROUND: Sediment budgets for inlets and adjacent beaches provide a conceptual and quantitative model of sediment-transport magnitudes and pathways for a given time period. Sediment budgets are a framework for understanding a complex inlet and coastal system, whether in its natural or engineered condition. Often, the natural condition is studied to gain background information necessary for evaluating the inlet and adjacent beach response to coastal engineering projects (see Komar 1996, 1998) for an overview of concepts and applications). Sediment budgets can enter at any of four stages in project development:

a. *Existing Condition.* A sediment budget for the existing condition is the most common type. This budget forms the basis for evaluating the impacts of planned engineering activities and the natural evolution of the inlet or coast.

b. *Historical (pre-engineering activity) Condition.* This budget is typically constructed for comparison with the existing-condition budget. A common application of the two budgets is a Section 111 or similar study, in which the impacts of inlet-related engineering activities (Federal navigation projects) on the adjacent beaches are estimated.

c. *Forecast Future Condition.* Adapting and extrapolating the existing-condition sediment budget can assess the potential response to future projects or modifications.

d. *Intermediate Condition.* Sediment budgets representing other periods create a model of inlet or coastal evolution through time, which may lend insight to interpreting present or future evolution. As examples, intermediate-condition sediment budgets may document evolution of the inlet from initial formation to a quasi-equilibrium state, or they may reveal a picture of long-term natural bypassing through a cycle of channel migration and welding of a portion of the ebb-tidal shoal to the adjacent beach.

THEORY: A sediment budget is a tallying of sediment **gains** and **losses**, or **sources** and **sinks**, within a specified control volume (or cell), or series of connecting cells, over a given time.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 1000**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Formulation of Sediment Budgets at Inlets (CETN IV-15; revised)**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Rosati, Julie Dean, and Kraus, Nicholas C.**		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**20**	

There are numerous ways of formulating a sediment budget (e.g., *Shore Protection Manual* 1984; Jarrett 1991; Bodge 1999; Mann 1999). The difference between the sediment sources and the sinks in each cell, hence for the entire sediment budget, must equal the rate of change in sediment volume occurring within that region, accounting for pertinent engineering activities. The sediment budget equation can be expressed as,

$$\sum Q_{source} - \sum Q_{sink} - \Delta V + P - R = Residual \qquad (1)$$

in which all terms are expressed consistently as a volume or as a volumetric change rate; Q_{source} and Q_{sink} are the sources and sinks to the control volume, respectively; ΔV is the net change in volume within the cell; P and R are the amounts of material placed in and removed from the cell, respectively; and *Residual* represents the degree to which the cell is balanced. For a balanced cell, the residual is zero. Figure 1 schematically illustrates the parameters appearing in Equation 1. For a reach of coast consisting of many contiguous cells, the budget for each cell must balance in achieving a balanced budget for the entire reach.

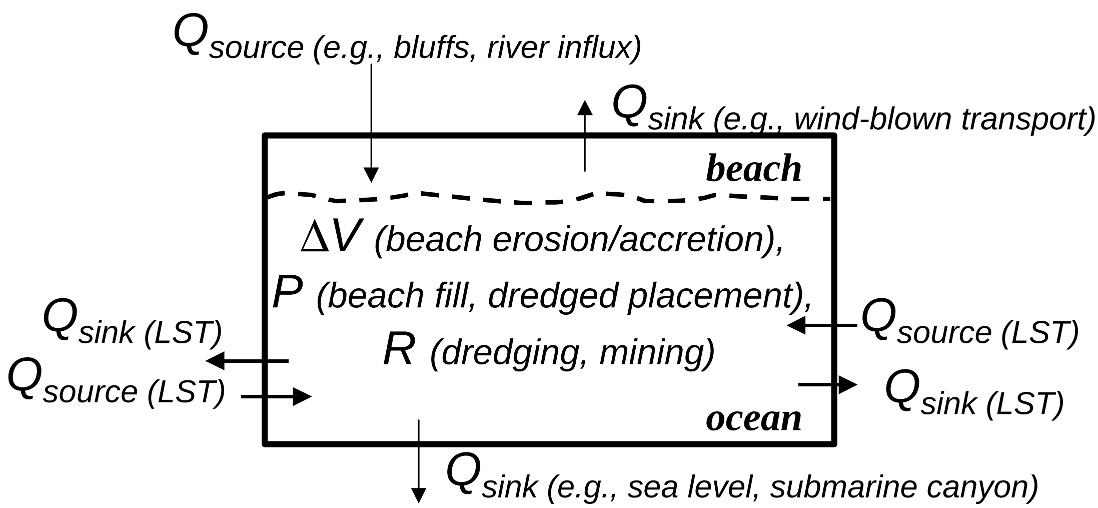

Figure 1. Sediment budget parameters as may enter Equation 1

As noted in Figure 1, **sources** to the sediment budget include longshore sediment transport, erosion of bluffs, transport of sediment to the coast by rivers, erosion of the beach, beach fill and dredged material placement, and a decrease in relative sea level. Examples of sediment budget **sinks** are longshore sediment transport, accretion of the beach, dredging and mining of the beach or nearshore, relative sea-level rise, and losses to a submarine canyon.

If inlets are located within the domain of a coastal sediment budget, they present significant challenges because inlets and the adjacent beaches are connected. Inlets increase the complexity of sediment budgets for several reasons. First, sediment-transport magnitudes and pathways are difficult to define at inlets, even in a relative sense. Flood and ebb currents, combined waves and currents, wave refraction and diffraction over complex bathymetry, and engineering activities complicate transport rate directions and may increase or decrease their magnitudes. Because the pathways of sediment movement in the vicinity of an inlet can be circuitous, equations

describing the sediment budget of regions directly adjacent to the inlet are not unique (that is, different formulations are possible).

Coastal engineering analyses involve two types of longshore transport rates. The *net* longshore transport rate is defined as the difference between the right- and left-directed littoral transport over a specified time interval for a seaward-facing observer,

$$Q_{net} = Q_R - Q_L \qquad (2)$$

in which the leftward-directed transport Q_L and rightward-directed transport Q_R are taken as positive. The *gross* longshore transport rate is defined as the sum of the right- and left-directed littoral transport over a specified time interval for a seaward-facing observer,

$$Q_{gross} = Q_R + Q_L \qquad (3)$$

An inlet channel has the potential to capture the left- and right-directed components of the gross longshore transport of sediment, and the inlet system may bypass left- and right-directed longshore transport. Thus, knowledge of the net and gross transport rates, as well as the potential behavior of the inlet with respect to the transport pathways, may be required to correctly represent transport conditions within the vicinity of inlets, as emphasized by Bodge (1993).

STEPS IN FORMULATING A SEDIMENT BUDGET: In the following section, a methodology for creating a sediment budget is outlined.

Step 1: Consider a Regional Approach. For accurate representation of a local project area, especially in the vicinity of inlets, a sediment budget is formulated with its lateral boundaries located well beyond the apparent (expected) local project boundaries. A regional sediment budget might include one or more barrier islands, several inlets, headlands, and pocket beaches to fully capture the past and potential future changes in the sediment transport.

In the United States, inlets have been stabilized by jetty construction for periods typically ranging from decades to centuries. Such navigation projects have the potential to influence the transport of sediment on the adjacent beaches for many kilometers, a distance that may extend well beyond what is considered the direct area of the inlet. Thus, a regional sediment budget that incorporates adjacent barrier islands, bay regions, underlying geology, estuarine and riverine impacts, and perhaps several inlets, may be required to assess the impacts of past and future projects. Engineering activities at navigable inlets and other data required for an inlet sediment budget have a high degree of uncertainty. Examples of these data include dredging quantity, location, and littoral quality; adjacent beach-fill volumes, initial cross-shore and longshore adjustment, and littoral quality; and limited ebb- and (more commonly) flood-tidal shoal bathymetric coverage. In addition, uncertainty is introduced by the need to assess the degree to which structures block, reduce, and modify the sediment-transport pathways and magnitudes (Kraus and Rosati 1998a, 1999).

In one of the earliest works that may be considered a regional sediment budget, Caldwell (1966) summarizes a study performed in the 1950s by the New York District of the Corps of Engineers for the north New Jersey coast (U.S. Army Corps of Engineers 1957, 1958). The budget, formulated by examining changes in shoreline position, served as a "field laboratory of shore processes" with the objective of examining alternatives to mitigate for erosion. This celebrated study deduced a regional divergent nodal point in net longshore transport direction at Mantoloking, located just north of Dover Township. Net longshore transport to the north increased with distance north from Mantoloking because of the sheltering of waves out of the north by Long Island, New York. The budget considered net and gross longshore sand transport for this 190-km reach including 10 inlets over time intervals of 50 to 115 years.

Another example of a regional sediment budget is that of Jarrett (1977, 1991) for the North Carolina shoreline, including three barrier islands and two inlets. Mann (1993) discussed use of a "near-field" versus "regional" sediment budget. The near-field sediment budget represents local (project area) sediment sources, sinks, and pathways. The regional sediment budget combines the near-field budget with the sediment-transport processes occurring on the adjacent shorelines. For development of inlet sand management strategies (and estimating the inlet's littoral impacts), Mann recommends consideration of a regional sediment budget so that interactions of the inlet (and any proposed modifications) on the adjacent shorelines can be assessed. Although it may be difficult to define and balance all sources, sinks, and sediment-transport pathways within a regional context, this comprehensive approach may allow the practitioner to recognize a source or sink of sediment hundreds of kilometers away that has a potential significance to the project area (Komar 1998).

Step 2: Develop a Conceptual Budget. Kana and Stevens (1992) introduced a "conceptual sediment budget," which they recommend developing in the planning stage prior to making detailed calculations of individual sources and sinks. The conceptual sediment budget is a qualitative model giving a regional perspective of the inlet interaction with beach processes, containing the effects of offshore bathymetry (particularly shoals and, therefore, wave-driven sources and sinks), and incorporating natural morphologic indicators of net (and gross) sand transport. The conceptual model may be put together in part by adopting sediment budgets developed for other sites in similar settings and incorporates all sediment sinks, sources, and pathways. The conceptual model should be developed initially, perhaps based upon a reconnaissance study at the site as part of the initial data set. Once the conceptual sediment budget has been completed, data are assimilated to validate the model rather than to develop the model.

Step 3: Ensure Compatibility of Temporal and Spatial Scales. In a discussion of the planning process for coastal projects, Kraus (1989) advocated the concept that the temporal and spatial scales of data used to develop and drive a model (whether a numerical, analytical, physical, or conceptual model) must be commensurate with these scales of the model itself. For example, a sediment budget developed based on pre- and post-storm data representing a day-to-month-length temporal scale within the immediate vicinity of the inlet should not be extrapolated to forecast to temporal scales of years and decades for a region extending over several barrier islands. Similarly, a sediment budget developed based on a 50-year period cannot adequately bracket the seasonal fluctuation observed locally at the project site. Sediment budgets are

commonly required to represent periods of engineering and geomorphic significance, from 3-5 years (dredging cycle at inlets) to 30-50 years (project life span; time scale for cyclic ebb-shoal welding). Data sets reflecting the longer durations are required to develop the sediment budget for spatial scales reflecting a regional approach. However, seasonal and year-to-year variability should be considered and can contribute to the uncertainty in a sediment budget or form the basis for a sensitivity analysis.

Step 4: Delineate Littoral Cells. A littoral cell (or "control volume") defines the boundaries for each sediment budget calculation and denotes the existence of a complete self-contained sediment budget within its boundaries (Dolan et al. 1987). Bowen and Inman (1966) introduced the concept of littoral cells (Inman and Frautschy 1966) within a sediment budget. The southern California coast lends itself to this concept, with evident sources (river influx, sea-cliff erosion), sinks (submarine canyons), and coastal geology (rocky headlands) defining semicontained littoral cells and subcells (Komar 1996, 1998). A littoral cell can also be defined to represent a region bounded by assumed or better known transport conditions or natural and engineered features such as the average location of a nodal region (zone in which $Q_{net} \sim 0$) in net longshore transport direction or a long jetty.

Step 5: Consider Net and Gross Transport Rates. For cells of the regional budget that may capture a portion of the left- or right-directed transport, both of these components must enter in the formulation. Examples include submarine canyons and inlet channels that capture both left- and right-directed transport; inlet weirs that may trap a portion of the left- or right-transport rate; and initial beach response at a long groin or headland feature, which may indicate accretion associated with left- and right-directed transport. Caldwell (1966) considered the gross transport rate as a potential indicator of shoaling for inlets in the vicinity of Cape May, New Jersey. Jarrett (1977, 1991) balanced potential longshore energy flux calculations with measured beach and tidal inlet change to solve for net and gross rates of longshore sand transport. Bodge (1993) focused on the inlet and its adjacent beaches and emphasized the importance of considering the gross components of longshore sediment transport, especially for inlets that act as sediment sinks. The gross transport rate can also provide an upper limit for the net, left-, and right-directed rates (*Shore Protection Manual* 1984).

Step 6: Assign Values and Uncertainties. Known, estimated, or easily obtained values and their associated uncertainties are assigned to source, sinks, and engineering activities within the sediment budget. This step should represent a low level of effort to assess quickly the integrity of the macrobudget (discussed below) and to uncover problems before detailed analysis begins. Detailed data analysis is discussed in Step 8 (below).

Every measurement has limitations in accuracy and contains a certain error. For coastal and inlet processes, typically direct measurement of many quantities cannot be made, such as the long-term longshore sand transport rate or the amount of material bypassing a jetty. Values of such quantities are obtained with predictive formulas or through estimates based on experience and judgment, which integrate over the system. Therefore, measured or estimated values entering a sediment budget can be considered as consisting of a best estimate and uncertainty. Uncertainty, in turn, consists of *error* and *true uncertainty*. A general source of error is limitation in the measurement process or instrument. True uncertainty is the error contributed by unknowns that

may not be directly related to the measurement process. Significant contributors to true uncertainty enter through natural variability and unknowns in the measurement process. These include temporal variability (daily, seasonal, and annual beach change); spatial variability (longshore and across shore); definitions (e.g., shoreline orientation, direction of random seas); and inability to quantify a process, such as the volume of material pumped to a beach or the sediment pathways at an inlet. Other unknowns can enter, such as grain size and porosity of the sediment (especially true in placement of dredged material). For further discussion and example uncertainty calculations, the reader is directed to CETN-IV-16 (Kraus and Rosati 1998a), Kraus and Rosati (1999), and Mann (1999).

Step 7: Formulate a Macrobudget. A macrobudget is a quantitative balance of sediment inflows, outflows, volume changes, and engineering activities within the regional conceptual budget. Essentially, the macrobudget solves the budget with one large cell (perhaps by temporarily combining many interior cells) that encompasses the entire longshore and cross-shore extents of interest. Balancing the macrobudget reduces the possibility of inadvertently including potential inconsistencies in a detailed or full budget (Kraus and Rosati 1999).

Step 8: Refine Estimated Values and Uncertainties. Once the macrobudget has been balanced, detailed analysis for all inflows, outflows, volume changes, and engineering activities pertaining to each individual cell may commence. Values entered for the macrobudget can serve as first estimates for the detailed budget, providing at least the expected order of magnitude for final values. The types of data sets that are available for refining sediment budget quantities are discussed below.

- **Aerial Photography.** Interpretation of aerial photographs offers the best means of obtaining broad qualitative understanding of the site. As examples, photographs of sites with relatively clear water can identify the planform shape of the flood-tidal shoal to estimate its volume if more quantitative data are unavailable. The pattern of wave breaking over the ebb-tidal shoal indicates the planform shape of this feature, which might lend qualitative understanding of its interaction with adjacent beaches and of sediment pathways. Overwash fans on adjacent barrier islands indicate pathways for loss of sediment to the coastal littoral system, from which quantification of volumes might proceed. Shoals adjacent to jetties might indicate sediment transport over and through the structure as a potential sediment-transport pathway. In a more quantitative analysis, controlled and rectified aerial photographs are commonly interpreted to identify the berm or high-water line (HWL) shoreline position (see CETN-II-39 "Interpretation of Shoreline-Position Data for Coastal Engineering Analysis," Kraus and Rosati 1998b).

- **Beach-Profile Surveys.** Volume change ΔV in the beach can be obtained accurately through repetitive surveys of the beach profile. The volume change for a given profile is typically assumed to represent the region of beach of length Δx between adjacent profile lines. Both the elevations B of the berm and of the profile closure depth D_C can be estimated from beach-profile surveys if the profile data are sufficiently accurate and well controlled. The active berm crest is a discernible morphologic feature on the profile representing the upward limit reached by the water under normal tide and water-level conditions. The profile may have two berm crests if the beach has recently accreted, and the elevation of the seawardmost

feature should be noted. The depth of closure is located where no significant depth changes occur over times of engineering significance (typically, 10 to 50 years) (see Hallermeier (1978); Birkemeier (1985); Kraus, Larson, and Wise (1998)). Kraus, Larson, and Wise (1999) discuss the depth of closure in detail and extend its definition to cover varied conditions as encountered in engineering practice. Profile surveys performed near structures may indicate their condition. For example, a jetty that allows sediment transport over and through it might be indicated by a berm-crest elevation adjacent to the structure that is comparatively lower than the berm crest further away from the structure. Similarly, surveys close to structures reveal whether the profile deviates from the average shape far from the structures, improving estimates of sand volume. The investigator should be cautious in interpreting beach-profile data near the inlet because of migrating shoal features that may affect the profile shape.

- **Shoreline-Position Data.** Shoreline-position data may be obtained from analysis of topographic and HWL surveys, aerial photographs, beach-profile surveys, and bathymetric data (Anders and Byrnes 1991; Byrnes and Hiland 1995). In a qualitative manner, beach morphology indicated by shoreline position may imply sediment-transport pathways or controls. As examples, a salient or bulge-type feature in the shoreline downdrift of an inlet may represent the location for ebb-shoal bypassing to the adjacent beach. Rocky headlands and outcroppings indicate geologic controls on sediment-transport pathways.

  As quantified in a sediment budget, the change in shoreline position Δy averaged over a given longshore distance Δx can be converted to a volume change by assuming that the shoreline translates parallel to itself over an active depth D_A, given by

$$D_A = B + D_c \tag{4}$$

  in which B is the elevation of the seawardmost active berm relative to a datum, and D_C is the depth of closure measured from the same datum.[1] The volume change[2] ΔV over a time interval Δt is given by

$$\Delta V = \frac{\Delta y \Delta x D_A}{\Delta t} \tag{5}$$

  If available, the impoundment rate at a shore-perpendicular structure such as a groin or jetty that is sandtight gives an estimate of the longshore sediment-transport rate.

[1] Estimates of uncertainties and their significance in coastal-sediment budgets are described in CETN IV-16 (Kraus and Rosati 1998a).
[2] Comparison of a shoreline position derived from aerial photography with a shoreline position derived from beach-profile surveys should account for possible differences in the vertical datums to which each is referenced. For example, it is likely that an aerially derived shoreline position represents a berm crest or HWL position, whereas a beach-profile shoreline may represent a zero elevation relative to a standard datum (e.g., National Geodetic Vertical Datum, or Mean Sea Level). See CETN II-39 (Kraus and Rosati 1998b).

- **Bathymetry.** Historical and recent bathymetric data sets are a valuable resource for determining the rate of volume change in the inlet channel and on the ebb- and flood-tidal shoals. If coverage is sufficient, differences in bathymetric surfaces give the subaqueous volume change on the adjacent beaches and channel and ebb- and flood-tidal shoals. It is noted that, in the past, typical bathymetric coverage has been limited to the inlet channel. However, the benefits of increasing the survey area to include the ebb- and flood-tidal shoals far outweigh the additional costs, particularly in view of reductions in the cost of bathymetric surveys (e.g., SHOALS bathymetric survey system, Parson and Lillycrop 1998). Bathymetric data can also indicate sediment-transport pathways. As examples, a finger shoal extending from the tip of a jetty likely indicates a dominant sediment-transport pathway, and the morphologic form of an ebb-tidal shoal that connects to the adjacent beaches may indicate inlet bypassing. Aerial photography of flood-tidal shoals at different but known tidal elevations can be referenced to create a contour map of the shoals, and thereby to estimate a shoal volume.

- **Engineering History.** Engineering activities of significance to a sediment budget fall into two categories: (a) those that are of a descriptive nature and must be quantified within the sediment budget and (b) those that are a priori quantified. Rehabilitation of a jetty is an example of a descriptive activity that requires quantification. The morphology of the inlet and adjacent beach before and after structure rehabilitation, as well as the type of rehabilitation (e.g., raising the jetty crest elevation, inserting a sandtight core, adding armor stone), and other pertinent data sets indicate the effectiveness of the structure. Consideration should be given as to the degree of sediment transport through, over, and around the structure before and after rehabilitation. Another example of descriptive data is the grain size of dredged material placed on the adjacent beaches. From this information, the engineer must estimate percentage of material that would remain in the active littoral zone.

  Engineering activities that are a priori quantified (although sometimes only partially) include the following: volumes, locations, and times of dredged and placed material; volume of material mined from ebb- and flood-tidal shoals, the locations, and times of mining; configuration of the placement; volume of fill on adjacent beaches and its placement location and time period of placement; and records of mechanical bypassing (volume, placement location, and time periods). These quantities will enter the sediment budget calculations by adjusting measured volume changes to account for either the removal or placement of material through engineering activities. The adjustment of an initial beach fill can be used to infer rates of longshore and cross-shore sediment transport.

- **Coastal Processes.** Data on the acting coastal processes are a resource for understanding and quantifying inlet- and sediment-transport pathways and quantitites. Examples are discussed here.

  Net, left-, and right-directed potential longshore sand-transport rates can be calculated from wave gauge, Wave Information Study (WIS), and Littoral Environment Observation (LEO, see Schneider (1980)) wave height, period, and direction data. CETN-II-19 (Gravens 1989) discusses the methodology for calculating net potential longshore sand-transport rates from WIS data. The components of the net transport, directed to the left or right as noted by a

shore-based observer, can be calculated by using the left- or right-directed waves, respectively, with the methodology as outlined in CETN-II-19. Often the magnitudes of the calculated net, left-, and right-directed potential longshore sand-transport rates do not agree with accepted values for the site. However, the relative magnitude between the left- and right-directed transport can be applied in a sediment budget with an accepted value for net longshore sediment transport to adjust the magnitudes. Wave height, period, and direction data allow construction of wave rays or orthogonals (*Shore Protection Manual* (SPM) 1984, Chapter 2) as indicators of pathways of sediment transport.

Inlet flow speed and direction data as indicated by current meters or drogue movement give the relative magnitude of sand-transport rates and pathways. For example, measurements of the current from Ocean City Inlet, Maryland, indicated that the flow to the northern part of the bay was considerably greater than that to the southern part (Dean and Perlin 1978). This information can be adapted to proportion the relative magnitude of the bay-directed sand transport to different parts of the bay.

The rate of relative sea-level rise may represent a contributing factor to the observed beach change. The long-term beach loss Δy_{sl} because of an increase S in relative sea level is (Bruun 1962, 1988; Komar 1998)

$$\Delta y_{sl} = \frac{L_c}{B + D_c} S \tag{6}$$

for which L_c is the cross-shore distance from datum to the long-term depth of closure D_c .

Other types of coastal process data useful for formulation of a sediment budget include the following:

- River-flow speed, fluvial sediment grain size, and sediment availability as a possible sediment source to the coastal environment.

- Wind speed and direction, sediment grain size, and availability as a potential aeolian sediment source to or a sink from the coastal environment.

- Sediment characteristics (e.g., median size, size distribution, mineral content) as natural tracers for sediment movement.

Step 9: Use Residuals to Balance Individual Cells. As presented in Equation 1, balanced individual sediment budget cells and the macrobudget sum to zero all sources, sinks, and volume changes associated with engineering activities. Inman (1991) considered recording an unbalanced sediment budget cell (a cell with a nonzero residual in Equation 1) as a region requiring more definition and investigation of the unknown processes. Knowledge of the residual may also be useful to bracket the uncertainty range for the data sets (Kraus and Rosati 1999).

Step 10: Conduct Sensitivity Testing. Once a sediment budget has been created, it can be copied and modified to evaluate the impact of any assumptions or refinements to the underlying data on the final sediment budget. Different data sets for the same project site can be applied to evaluate seasonal variations in beach change and transport rate direction and magnitude. A balanced budget representing a historical time period can be copied and altered to represent a potential future with-project condition.

Example 1: Develop a conceptual sediment budget for the period 1938 to 1979 for the regional littoral system of Shinnecock Inlet, Long Island, New York. This region extends east of Shinnecock Inlet to Montauk Point and west of Shinnecock Inlet to Moriches Inlet.

Background Information: Shinnecock Inlet, located on the South Shore of Long Island, New York, was formed during a hurricane in September 1938 (Figure 2). The west jetty was initially constructed by New York State in 1947 and was extended from 1953 to 1955, and the east jetty was constructed from 1952 to 1953. Shinnecock Inlet's littoral system is bounded to the east by Montauk Point, a location at which net longshore sediment transport is negligible because of its shoreline orientation and fetch distance from the mid-Atlantic coast. West of Montauk Point, 10- to 21-m-high bluffs extend for 8 km and are a source of sediment roughly estimated as 35,000 cu m/year based on analysis of profile data. The U.S. Army Engineer District, New York, formulated a sediment budget for the inlet (U.S. Army Corps of Engineers 1987). Estimates are available for the net longshore sand-transport rate 1 km east of the inlet (230,000 cu m/year), the ebb-shoal volume change (77,000 cu m/year), the flood-shoal volume change (15,000 cu m/year), and the net longshore sand transport 1.8 km west of the inlet (189,000 cu m/year).

Nersesian and Bocamazo (1992) developed a preliminary sediment budget in which the net transport east of Shinnecock was 281,000 cu m/year, the ebb and flood shoal captured 77,000 and 15,000 cu m/year, respectively; and transport west of the inlet was 189,000 cu m/year. Kana (1995) estimated net transport rates 3 km east and 2 km west of Shinnecock Inlet as 219,000 and 104,000 cu m/year, respectively. A seaward bulge located approximately 2 km downdrift of Shinnecock Inlet is apparent in the 1979 shoreline position, indicating a possible region of sediment exchange between the ebb-tidal shoal and the downdrift beach. West of Shinnecock Inlet, the Westhampton barrier island extends for 25 km to Moriches Inlet. Moriches Inlet was formed in March 1931 and migrated 1,200 m to the west before it closed naturally in May 1951. Jetties were constructed in 1952 to 1953 at the position of the former inlet, and through dredging and a minor storm, the inlet reopened. Taney (1961) estimated net transport rates at Moriches Inlet as 229,000 cu m/year.

Conceptual Sediment Budget: Figure 2 shows the conceptual sediment budget developed from the information presented. Applying this information with Equation 1 indicates that the beaches between Shinnecock Inlet and Montauk Point and between Moriches and Shinnecock inlets most likely have eroded during the subject period unless a significant quantity of beach fill was placed. Some volumes are not quantified (e.g., beach losses because of relative sea-level rise Q_{sl}; beach-fill placement rate P; dredging (removal) rate R) but are represented for completeness.

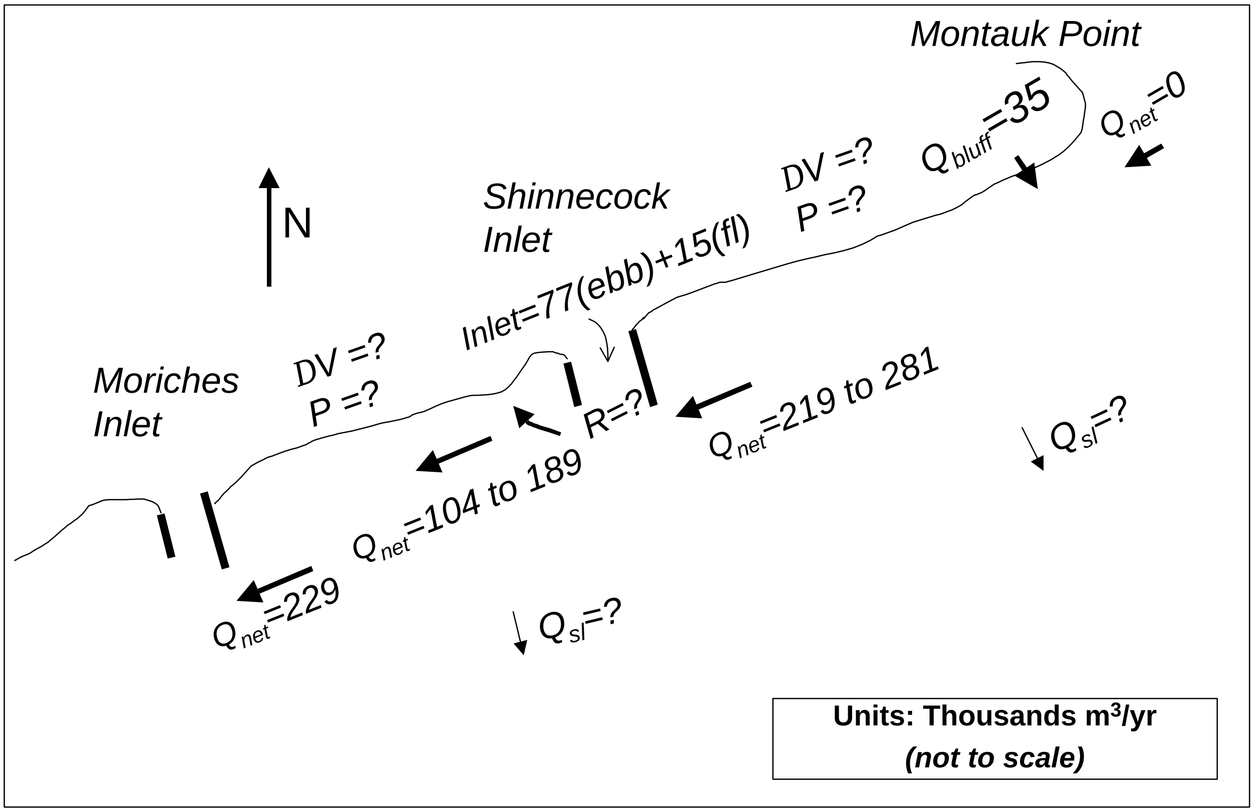

Figure 2. Conceptual sediment budget for Shinnecock Inlet, New York

Example 2: Refine the conceptual budget for Shinnecock Inlet and the beaches ±3.2 km east and west of the inlet. Because of space limitations, uncertainty in the sediment budget will be omitted (refer to CETN-IV-16 for estimating uncertainty within a sediment budget).

Background Information: The refined conceptual budget is shown in Figure 3, and details of its formulation are presented here. At 3.2 km east of the inlet, wave refraction modeling indicated that the ratio of Q_R to Q_L was approximately 1.9. The same ratio west of the inlet, also estimated from wave refraction modeling, was 1.8. These ratios indicate a westerly directed net transport that is slightly greater at the eastern boundary as compared with the western boundary. Based on profile-survey data, the berm-crest level was 3.5 m relative to National Geodetic Vertical Datum (NGVD), and the depth of closure was 7.0 m NGVD. The average shoreline change rate $\Delta y/\Delta t$ for Adjacent Beach 1 (from inlet to 3.2 km east, hereafter noted as A1) was 1.40 m/year, and the same quantity for Adjacent Beach 2 (from inlet to 3.2 km west, noted as A2) was –1.43 m/year. Beach-fill placements for A1 and A2 were 13,000 and 25,000 cu m/year, respectively. The rate of relative sea-level rise was 0.003 m/year, and the distance from datum to the depth of closure L_c was approximately 760 m for A1 and A2. The inlet channel and shoals had a net volume change of 111,000 cu m/year, with dredging averaging 2,400 cu m/year (Moffatt and Nichol Engineers & URS Consultants 1999).

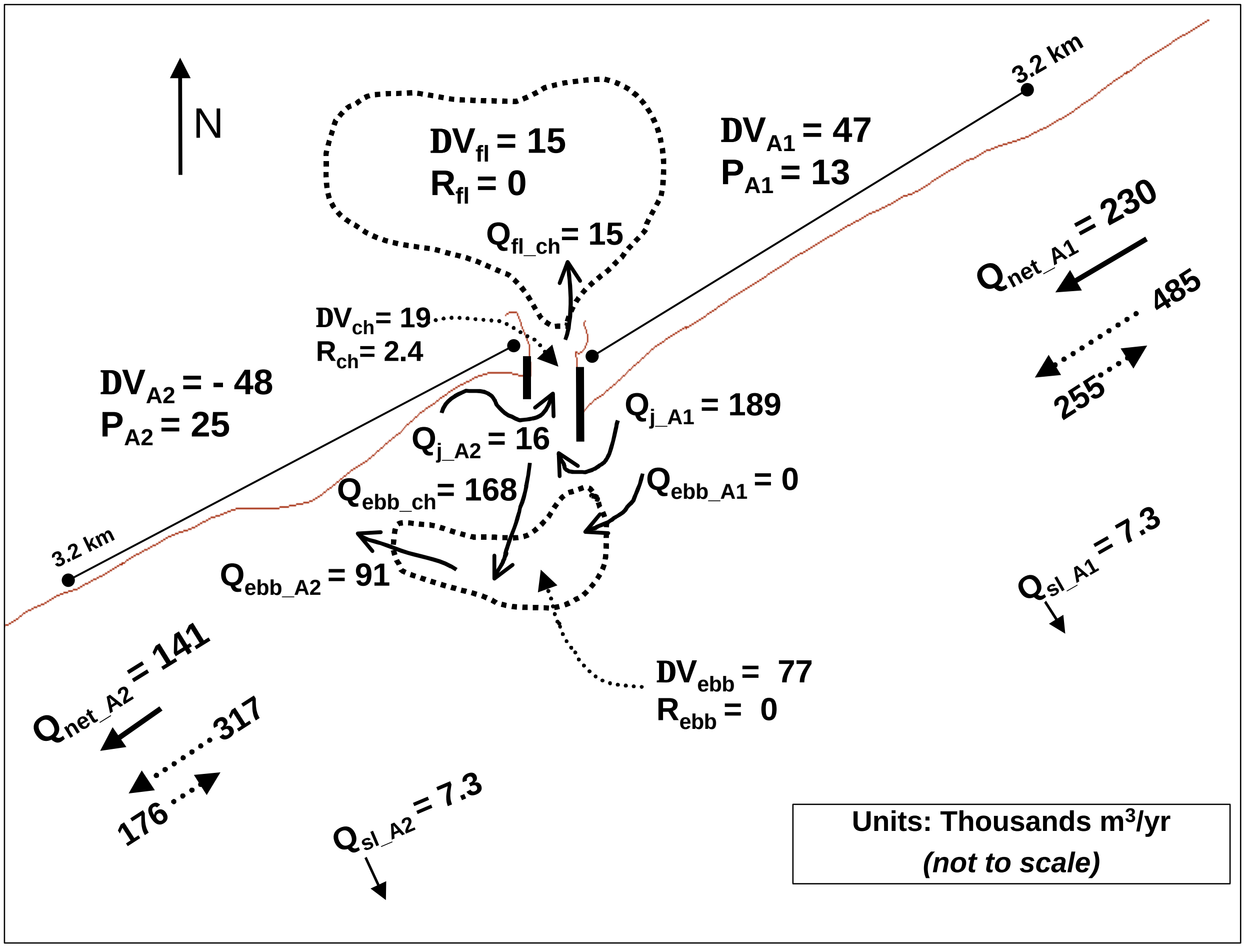

Figure 3. Revised sediment budget for Shinnecock Inlet, New York

Calculations: Applying Equation 4 gives an active depth for A1 and A2,

$$D_A = B + D_C \quad = \quad 3.5 + 7.0 \quad = \quad 10.5\ m$$

The rate of volume change for A1 and A2 can be calculated with Equation 5,

$$\Delta V_{A1} = \frac{\Delta y \Delta x D_A}{\Delta t} \quad = \quad (1.40\ m/year)\ (3{,}200\ m) \quad (10.5\ m) \quad = \quad 47{,}000\ cu\ m/year$$

$$\Delta V_{A2} = \frac{\Delta y \Delta x D_A}{\Delta t} \quad = \quad (-1.43\ m/year)\ (3{,}200\ m) \quad (10.5\ m) \quad = \quad -48{,}000\ cu\ m/year$$

Losses because of relative sea-level rise can be estimated by Equation 6,

$$\Delta y_{sl\_A1} = \Delta y_{sl\_A2} = \frac{L_c}{B + D_c} S = \frac{760}{3 + 7.5}(0.003) = 0.22\ m/year$$

or,

$$Q_{sl\_A1} = Q_{sl\_A2} = (\Delta y_{sl\_A1}\ or\ \Delta y_{sl\_A2})(\Delta x)\ (D_A) = (0.22\ m/year)\ (3{,}200\ m)\ (10.5\ m) \sim 7{,}300\ cu\ m/year$$

The total change in volume for the inlet channel and shoals was given as 111,000 cu m/year. To fully develop the inlet sediment budget, this quantity will be proportioned between the ebb shoal, inlet channel, and flood shoal following the conceptual budget as guidance. Table 1 lists the rate of measured volume change ΔV, beach fill placed P, dredging (removal) R, and losses because of relative sea-level rise Q_{sl} for A1, each region of the inlet, and A2.

Table 1
Rates of Volume Change for Shinnecock Inlet Sediment Budget, 1938 to 1979 (thousands of cu m/year)

Control Volume	ΔV	P	R	Q_{sl}
A1 (Adjacent Beach 1)	47	13	0	7.3
Inlet: Ebb Shoal	77	0	0	0
Inlet: Channel	19	0	2.4	0
Inlet: Flood Shoal	15	0	0	0
A2 (Adjacent Beach 2)	-48	25	0	7.3

Refining Conceptual Sediment Budget. To formulate the inlet sediment budget, one can assume a rate of net transport at the updrift boundary, Q_{net_A1} = 230,000 cu m/year. This value is within the range identified in the conceptual sediment budget. In a more expanded analysis than presented here, a range of values for Q_{net_A1} can be applied in the sediment budget to examine fully the sensitivity of the inlet sediment-transport magnitudes and pathways to this parameter. The ratio of Q_R and Q_L was given as 1.9, and entering this value into Equation (2) gives,

$$Q_{net\_A1} = Q_{R\_A1} - Q_{L\_A1} = 1.9\ Q_{L\_A1} - Q_{L\_A1} = 0.9\ Q_{L\_A1}$$

$$230 = 0.9\ Q_{L\_A1}$$

$$Q_{L\_A1} = 255 \quad \text{and} \quad Q_{R\_A1} = 485$$

Considering the entire reach as the control volume forms a macrobudget. Applying Equation 1 gives,

$$\sum Q_{source} - \sum Q_{sink} - \sum \Delta V + \sum P - \sum R = Residual = 0$$

$$[Q_{net\_A1}] - [Q_{sl\_A1} + Q_{sl\_A2} + Q_{net\_A2}] - [\Delta V_{A1} + \Delta V_{A2} + \Delta V_{fl} + \Delta V_{ch} + \Delta V_{ebb}] + [P_{A1} + P_{A2}] - [R_{fl} + R_{ch} + R_{ebb}] = 0$$

$$[230] - [7.3 + 7.3 + Q_{net\_A2}] - [47 + -48 + 15 + 19 + 77] + [13 + 25] - [0 + 2.4 + 0] = 0$$

$$Q_{net\_A2} = 141$$

Applying Equation 2 at the western boundary gives,

$$Q_{net\_A2} = Q_{R\_A2} - Q_{L\_A2}$$
$$141 = 1.8\, Q_{L\_A2} - Q_{L\_A2}$$
$$Q_{L\_A2} = 176 \quad and \quad Q_{R\_A2} = 317$$

Now the control volume A1 can be considered. There are two unknowns, the rate of sediment transport around the east jetty, Q_{j_A1}, and sediment transport from A1 to the ebb-tidal shoal, Q_{ebb_A1} . Inspection of bathymetric charts and aerial photography shows no evidence of morphologic pathways (e.g., shoal features) from A1 to the ebb-tidal shoal. Thus, one can assume that $Q_{ebb\_A1} \sim 0$ and solve for Q_{j_A1} in Equation 1,

$$\sum Q_{source} - \sum Q_{sink} - \sum \Delta V + \sum P - \sum R = Residual = 0$$

$$[Q_{net\_A1}] - [Q_{sl\_A1} + Q_{j\_A1} + Q_{ebb\_A1}] - [\Delta V_{A1}] + [P_{A1}] = 0$$

$$[230] - [7.3 + Q_{j\_A1} + 0] - [47] + [13] = 0$$

$$Q_{j\_A1} = 189$$

Next a control volume for A2 is formulated, excluding the ebb-tidal shoal. There are also two unknowns for this control volume, the rate of sediment transport around the west jetty, Q_{j_A2} , and the rate of sediment transport bypassed from the ebb-tidal shoal to A2, Q_{ebb_A2}. A more detailed analysis of the shoreline position and beach-fill placement records for A2 indicates that $\Delta V - P = -16$ for the region east of the bulge in the 1979 shoreline position, and $\Delta V - P = -58$ for the region west of the bulge. As a first estimate, one can set $Q_{j\_A2} = 16$, implying that all sediment lost from the region east of the bulge moved around the west jetty. This assumption also implies that this morphologic feature represents a long-term nodal zone for net longshore sand transport. Using Equation 1 to solve for Q_{ebb_A2} gives,

$$\sum Q_{source} - \sum Q_{sink} - \sum \Delta V + \sum P - \sum R = Residual = 0$$

$$\left[Q_{ebb\_A2}\right] - \left[Q_{net\_A2} + Q_{j\_A2} + Q_{sl\_A2}\right] - \left[\Delta V_{A2}\right] + \left[P_{A2}\right] = 0$$

$$\left[Q_{ebb\_A2}\right] - \left[141 + 16 + 7.3\right] - \left[-48\right] + \left[25\right] = 0$$

$$Q_{ebb\_A2} = 91$$

in units of thousands of cubic meters.

The control volume for the ebb-tidal shoal now has one unknown, the rate of sediment transport from the channel to the ebb-tidal shoal, Q_{ebb_ch}. Applying Equation 1 gives,

$$\sum Q_{source} - \sum Q_{sink} - \sum \Delta V + \sum P - \sum R = Residual = 0$$

$$\left[Q_{ebb\_A1} + Q_{ebb\_ch}\right] - \left[Q_{ebb\_A2}\right] - \left[\Delta V_{ebb}\right] = 0$$

$$\left[0 + Q_{ebb\_ch}\right] - \left[91\right] - \left[77\right] = 0$$

$$Q_{ebb\_ch} = 168$$

The final unknown is the rate of sediment transport from the channel to the flood-tidal shoal, Q_{fl_ch}. Equation 1 applied to the inlet channel control volume gives,

$$\sum Q_{source} - \sum Q_{sink} - \sum \Delta V + \sum P - \sum R = Residual = 0$$

$$\left[Q_{j\_A1} + Q_{j\_A2}\right] - \left[Q_{ebb\_ch} + Q_{fl\_ch}\right] - \left[\Delta V_{ch}\right] - \left[R_{ch}\right] = 0$$

$$\left[189 + 16\right] - \left[168 + Q_{fl\_ch}\right] - \left[19\right] - \left[2.4\right] = 0$$

$$Q_{fl\_ch} = 15.6 \quad \sim \quad 15$$

The calculated value of Q_{fl_ch} = 15.6 approximately agrees with the assumed change in volume for the flood-tidal shoal, ΔV_{fl} = 15, indicating that there are no other significant sediment sources contributing to the growth of the flood-tidal shoal.

Discussion of Examples. These example problems illustrate one approach that can be taken for formulating a sediment budget. The following assumptions entered:

- Net longshore sand transport rate at the updrift boundary of the control volume was assumed to be 230,000 cu m/year.

- Rate of sediment transport from A1 to the ebb-tidal shoal was assumed to be negligible.

- Rate of sediment transport from A2 around the west jetty was assumed to be 16,000 cu m/year.

- Volume change rates for the ebb-tidal shoal, inlet channel, and flood-tidal shoal were assumed to be 77,000, 19,000, and 15,000 cu m/year, respectively.

- Uncertainties in quantities forming the sediment budget were omitted for this example problem because of limited space.

If one considers that the potential trapping capacity of the inlet is equal to Q_{gross} at the boundaries, an ideal (100-percent efficient) trap would collect sediment at the average rate of

$$Q_{L\_A2} + Q_{R\_A1} = 176 + 485 = 661{,}000 \text{ cu m/year}$$

However, the data indicate that the inlet trapped a smaller quantity,

$$\Delta V_{ebb} + \Delta V_{ch} + \Delta V_{fl} + R_{ebb} + R_{ch} + R_{fl} - P = 77 + 19 + 15 + 0 + 2.4 + 0 - 0 = 113{,}000 \text{ cu m/year}$$

Thus, this sediment budget indicates that the inlet trapped roughly 20 percent of the gross sediment transport from 1938 to 1979, although this percentage was most likely higher during early stages of inlet formation and decreased in later stages.

In a comprehensive analysis, the engineer should develop sediment budgets by giving a range of values for each of these quantities. Uncertainty in each quantity and in the assumptions listed above can be defined and calculated for each sediment budget alternative. Through sensitivity testing of assumed values, together with considering uncertainty in the known values, a suite of sediment budget alternatives is generated. The final sediment budget is comprised of these alternatives and, therefore, forms a representative model of likely sand-transport magnitudes and pathways.

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This CETN should be cited as follows:

Rosati, J. D., and Kraus, N. C. (1999). "Formulation of sediment budgets at inlets," Coastal Engineering Technical Note CETN-IV-15 (Revised September 1999), U.S. Army Research and Development Center, Vicksburg, MS. *http://bigfoot.wes.army.mil/cetn.index.html*

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